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Physical and Chemical Factors Affecting the Thermal IR Imagery of Ship Wakes

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A thermal infrared scanner mounted in an NRL RP-3A imaged the turbulent wake of the USNS HAYES in the vicinity of Phelps Bank in the southeast region of Nantucket Shoals. Thermal surface effects were determined for both natural wakes and those treated with small quantities (a few mg per m^2) of an organic material which produced a monomolecular film (slick) on the surface of the turbulent wake. Relevant meteorological and oceanographic parameters were measured simultaneously from shipboard.

Temperature profiles across the wake were determined at various distances behind the ship with a computer program applied to the digitized thermal IR images. These profiles along with corresponding water temperature data indicated that; (1) all wakes were cool relative to the ambient surface water, (2) the cool wake temperature was nearly the same as that measured at keel depth, (3) the thermal signatures of wakes treated with the surface film were more persistent than natural wakes, and the cool surface was maintained over a broader cross section of the treated wake, and (4) prior to dispersion by physical processes the thermal wake signatures

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broadened with age, an effect which was more pronounced for the film-treated wakes.

These observations were explained on the basis of wake hydrodynamics, wind-stress considerations, and surface film physics. The possible effects of film-forming ship effluents and natural organic film on thermal wake signatures are discussed.

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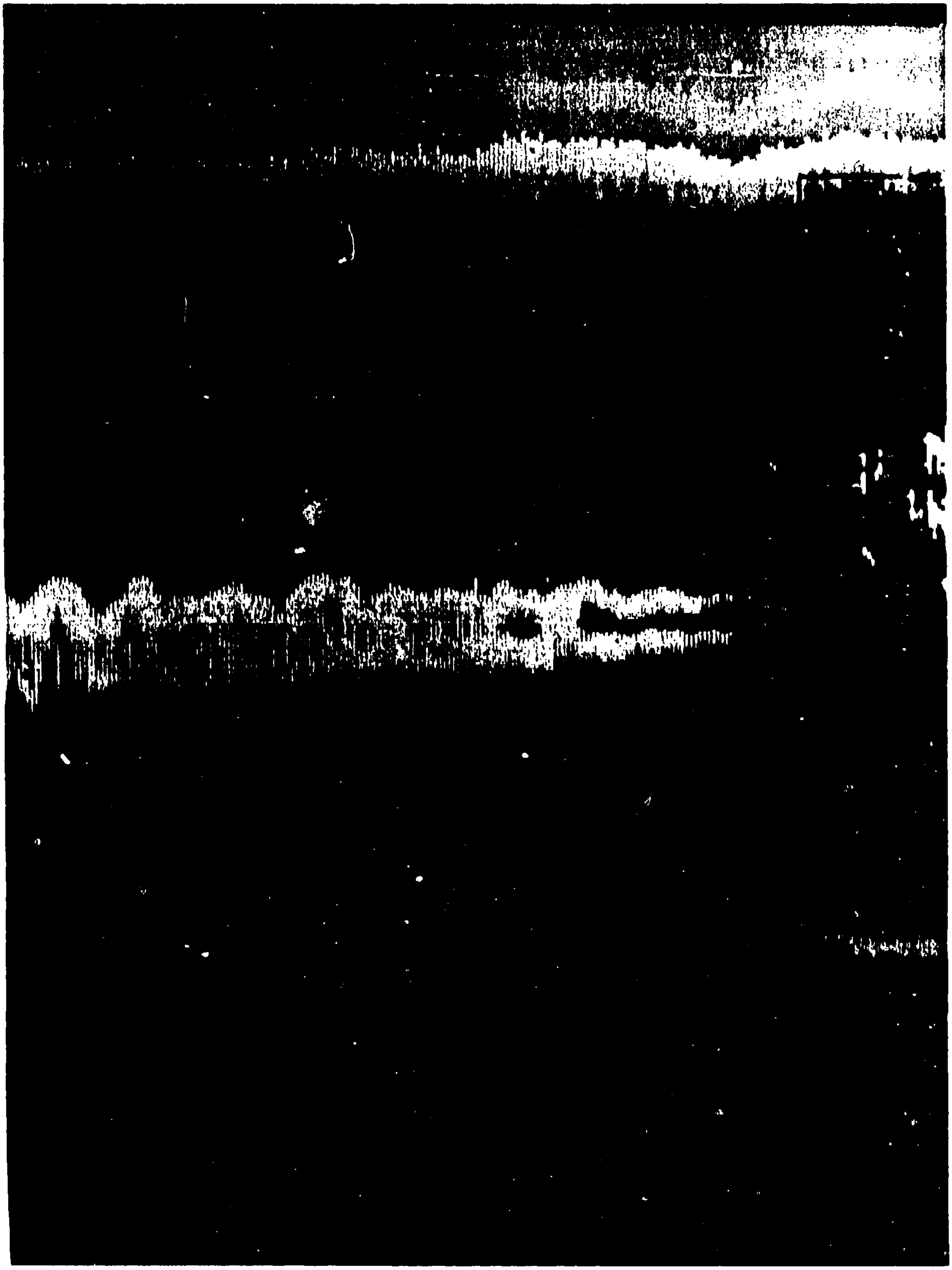

Frontispiece - Pseudo-colored thermal IR signature of wake of USNS HAYES at 1754z on 82-07-14 from an altitude of 1000 ft.

PHYSICAL AND CHEMICAL FACTORS AFFECTING THE THERMAL IR IMAGERY OF SHIP WAKES

BACKGROUND

Remotely sensed thermal IR signatures of ship wakes are highly variable in their persistence and temperature contrast with adjacent surface water. In general, the central core of the wake appears cooler than the surface water outside of the wake as measured by a thermal IR sensor. On occasion, wake edges or portions of the Kelvin wake may appear relatively warm. The explanations for these signatures are numerous and depend upon both meteorological and oceanographic parameters as well as ship operational characteristics. Since thermal IR is primarily responsive to thermal effects in the upper one millimeter of the sea, near-surface temperature gradients are important in determining the thermal signatures of ship wakes. The near-surface temperature gradients are in turn governed by the air-sea temperature difference, solar heating, evaporation, and mixing dynamics.

Another factor which influences the sea surface temperature is the presence of organic films at the air-sea interface. Such films may be monomolecular layers of the biogenic lipid, proteinaceous, and humic substances responsible for natural sea slicks, or they may be thicker layers of substances of anthropogenic origin, such as petroleum oils, galley effluents, hydraulic oils, or bilge water in overboard discharges from ships. Laboratory experiments have demonstrated that monomolecular organic films may cause either warmer or cooler water surface temperatures (Jarvis 1962; Katsaros and Garrett, 1982). For example, a large body of scientific literature deals with the retardation of evaporation by monomolecular layers of straight-chain compounds, the n-alkanols. Under certain environmental conditions these films may cause the temperature of a water surface to be higher than that of the film-free water surface adjacent to the film by inhibiting evaporative cooling (Grossman et al., 1969). However, the ability of a monomolecular surface film to retard evaporation is greatly dependent on the molecular geometry of its constituents. To retard the passage of water molecules, the constituents of the monolayer must be linear, have hydrocarbon chains of sixteen carbons or greater, and be packed tightly into a compressed film on the water surface. Molecules containing branched or permanently bent hydrocarbon segments as well as those whose hydrophilic group is ionized form monolayers which do not retard evaporation.

Most species of organic molecules found at the air-sea interface are nonlinear and incapable of adlineation into condensed films which inhibit evaporation. Although organic sea slicks readily form under calm conditions, natural organic substances at sea are seldom compressed into high surface pressure (low surface tension) monomolecular films on the sea surface (Barger et al., 1974). Even if linear molecules compressed tightly into a high pressure film existed or were added to the sea surface, wave induced surface dilations and convergences would interfere with the ability

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of the film to retard evaporation. Actually natural slicks usually appear slightly cooler than adjacent film-free surfaces when sensed by thermal infrared (Clark, 1967). Although the emissivity of a planar water surface is not altered by the presence of a monomolecular layer of organic material (Jarvis and Kagarise, 1961), the cool-surface effect of a few tenths of a degree is produced by an immobilization of the near surface water by the relatively rigid surface film (Jarvis, 1962). The uppermost sea surface layer which has been cooled by evaporation does not readily overturn, and the cooled water is held at the surface by the rigid organic film and its associated hydrogen-bonded aqueous surface boundary layer. The thickness of the surface layer of water affected by an organic monolayer due to long-range ordering effects has been determined by various investigators to vary between one and several hundred micrometers (Hühnerfuss and Alpers, 1983). The boundary layer thickness depends upon the nature of the experiments by which it was determined. For example, the sublayer thickness was determined to be about 30 micrometers in association with a flowing monolayer driven by a surface tension gradient (Schulman and Teorell, 1938).

Surface temperature effects caused by organic films either natural or due to ship effluents may explain certain thermal characteristics of ship wakes. During a previous ship overflight, wake imagery produced by the thermal IR scanner used in this study showed a gap of several ship lengths (330 m) before a sensible signature of the wake developed. In this case the apparent temperature difference between the cool wake and the surrounding water was no more than 0.5°C. One of the rationales for performing these experiments was the possible role of organic surface films in the development, temperature structure and persistence of the thermal IR signature of surface ship wakes. For example, as a wake ages the cooled wake signature which appears may be influenced in part by the development of a surface layer of natural organic film-forming material due to the surface convergence caused by wake dynamics. The combination of vertical transport coupled with the horizontal surface convergence of the film-forming molecules may be sufficient to produce a coherent film which immobilizes the normally free water surface and affects the distribution of cool surface water responsible for an IR signature. The experiments reported here were designed to test surface-film mechanisms as well as to determine other possible explanations for the thermal signatures of ship wakes.

EXPERIMENTAL DESCRIPTION

On 13 and 14 July 1982, several ship wake experiments were conducted, during which both natural and chemically treated wakes were investigated. The USNS Hayes (T-AGOR-16) produced a 40-minute, wake to the west of Phelps Bank, Nantucket Shoals on 13 July under a constant heading of 230° (Figure 1). On 14 July, two straight wakes were generated beginning just west of Phelps Bank with a ship's heading of 100° and a course heading of 89°. These latter wakes, 2 and 3, were separated by a 15-minute segment marked with a water-soluble dye and smoke.

The broad-line segments of each of the three wakes depicted in Figure 1 represent 20-minute wake treatments with oleyl alcohol (9-octadecen-1-ol, cis isomer). This water-insoluble, film-forming liquid spreads rapidly and spontaneously into a monomolecular organic film within the wake. The use of oleyl alcohol in these experiments was based upon criteria developed by

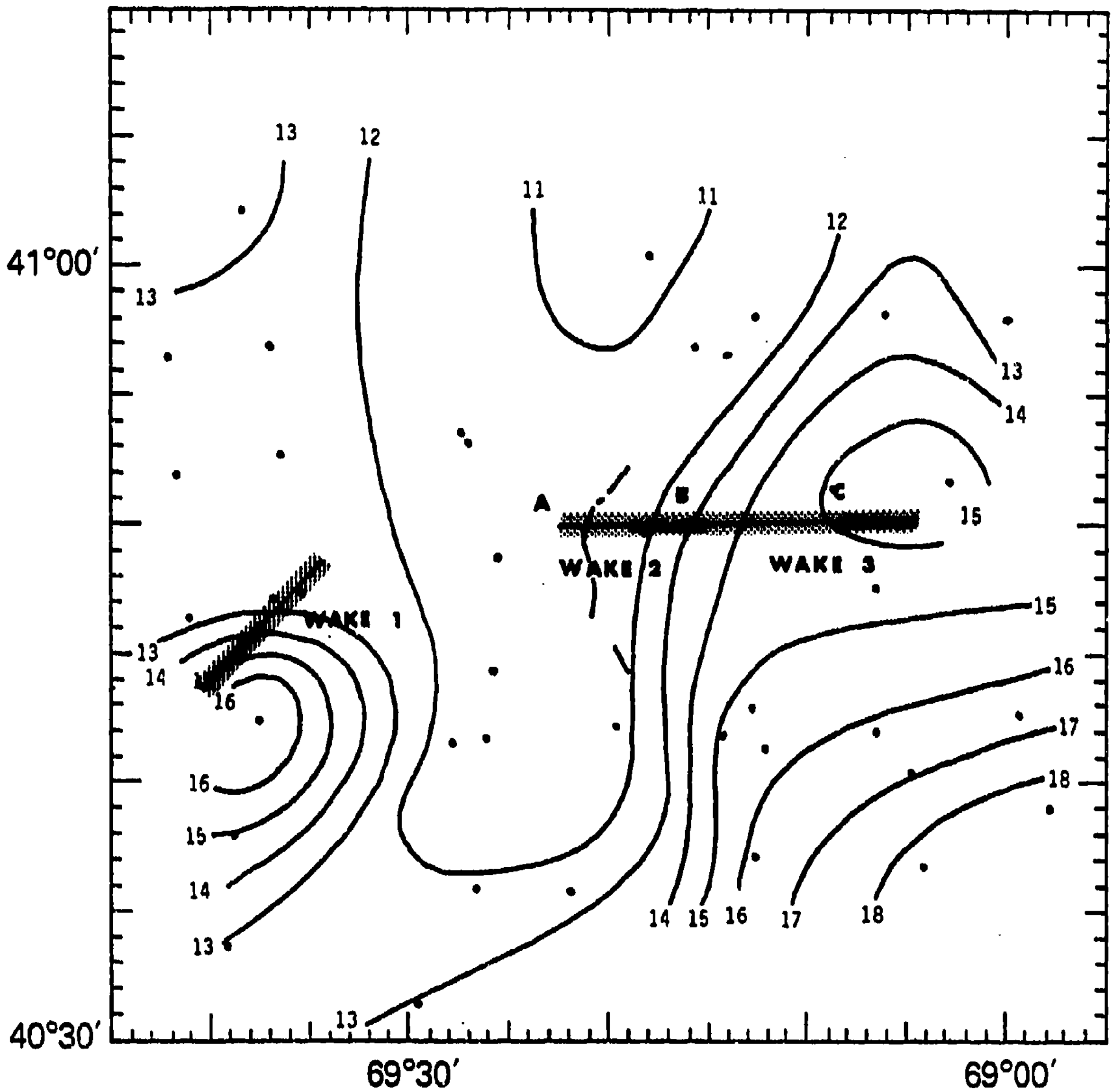

Figure 1. Wake experiment tracks on 82-07-13 (wake 1) and 82-07-14 (wakes 2 and 3) superimposed on tidally adjusted sea surface temperature field. The dark bands indicate portions of the wake treated with oleyl alcohol. A, B and C represents CTD casts near wakes 2 and 3 (plotted in Figure 4). The broken line near 69° 20'W represents Phelps Bank and Asia Rip.

Barger and Garrett (1974) for the selection of monomolecular film-forming agents to produce experimental slicks at sea for basic research and various practical applications. Additional information on sea-truth modification by organic films in conjunction with remote sensing research and ocean wave attenuation studies has been reported by Hühnerfuss and Garrett (1981) and by Garrett and Barger (1980).

The oleyl alcohol was dispensed from the stern of the USNS Hayes during the treated wake experiments at a constant flow rate using a pressurized tank. Calculation of the average surface concentration of oleyl alcohol in each wake was based upon the wake area and the quantity of material dispensed. The surface concentrations were 15.2, 7.3, and 6.2 milligrams per square meter for wakes 1, 2, and 3 respectively. A surface concentration of 1.5 $mg.m^{-2}$ is required to produce a uniform monomolecular film of oleyl alcohol (molecules close-packed to the maximum extent) on a planar surface.

Excess material over that required for a monomolecular layer is used for most organic surface film applications to replace film lost due to physical, chemical, or biological processes, such as wind-wave dispersion, evaporation, dissolution, photocatalytic oxidation, or biological utilization. The excess film-forming material does not spread over its own monomolecular layer on the water surface, but remains unspread as a thick lens in equilibrium with its monolayer, a property called autophobicity. When portions of the spread monolayer are displaced or lost from the air-water interface, the fluid, unspread, film-forming material quickly restores total film coverage and reestablishes the equilibrium film pressure. In addition, because oleyl alcohol is fluid both in bulk and in its spread monomolecular form, this equilibrium system responds rapidly to wave-induced expansions and contractions of the sea surface to maintain film coverage.

A Texas Instrument Company RS-310 thermal infrared scanner was flown over the ship wakes on a Navy RP-3A. The infrared scanner contains a 3 milliradian Hg-Cd-Te detector, with an 8-14 µm bandwidth, and when cooled to $77^{\circ}K$, can resolve $0.07^{\circ}C$. Data are recorded in analog on magnetic tape. The analog tape is digitized in the laboratory and analyzed and reproduced on a digital imaging system.

Calibration is accomplished by maintaining two reference black bodies in the field of view (FOV) at all times. The black bodies can be seen on each side of the imagery. Because of the Kennedy optics system used in the RS-310, the black bodies affect one third of the FOV on either side. Hence, only the center of the FOV is calibrated and useable. The black bodies maintained reference temperatures of $60^{\circ}F$ and $70^{\circ}F$, respectively. The scan rate is a constant 200 scans/second independent of altitude. Four wake overflights were made on 13 July of wake 1 and 10 overflights on 14 July of wakes 2 and 3. These overflights and the ship activities are summarized in the following wake chronologies.

WAKE EXPERIMENT CHRONOLOGIES

82-07-13
Wake #1

Natural wake   2015-2035z
Treated wake   2035-2055z;   15.2 $mg.m^{-2}$ of oleyl alcohol

Ship speed 8.5 kt using single starboard engine

COMEX 40° 48.48'N, 69° 34.30' W
FINEX 40° 43.68'N, 69° 40.53' W

Aircraft Overflights

Time	Altitude
2029 z	1500 ft.
2039	1500
2048	500
2052	1000

Bridge Log Data:

Sea, calm; Swell, 220°, 3 ft; Bar. 1016.2
T_a=80, T_w=50, T_{wet}=74°F

Seas very calm, slicked - a reverse condition in that the wake appeared to be less calm than surrounding sea surface

82-07-14

1715z	Natural wake #2
1735	Treated wake (smoke bomb)
1755	End treatment, 7.3 $mg.m^{-2}$ oleyl alcohol
1800	Dye marker
1815	Dye marker
1815	Natural wake #3
1835	Treated wake
1850	End exercise, 6.2 $mg.m^{-2}$ oleyl alcohol

Aircraft Overflights

Time	Altitude
1728z	1500 ft.
1734	500
1742	500
1747	1500
1754	1000
1803	500
1811	1500
1817	1000
1836	500
1840	1000

Ship Speed 8.8-9.5 kt using single starboard engine

Rippled and wave covered sea, wake appears calmer than surrounding seas

COMEX 40° 49.89' N, 69° 22.55' W
FINEX 40° 50.22' N, 69° 4.73' W

Bridge log data:

Wind, 090°, 8-12 kts; Sea (1-2 ft.), Swell, 190°, 4 ft.
Bar. 1020, T_a=70, T_w=50, T_{wet}=63°F

Thermal IR imagery of the ships's wake was obtained for the overflights listed in the wake experiment chronologies. The imagery was of variable quality, sometimes due to a drift of the aircraft away from the turbulent wake. Thus, data analysis and interpretation was concentrated on the untreated wake image taken on the flight at 1811Z and on the image of the treated wake at 1747Z, both flown at 1500 feet on 82-07-14. The latter wake had been treated with the organic film-forming chemical for a period of 13 min. at the time of the overflight. The imagery of these two flights are presented in Figure 2. The arrow indicates the point where treatment commenced as calculated from the time of treatment and the ship and aircraft speeds. A separate image (Figure 3) taken at 1754Z, 82-07-14 depicts the Hayes' wake treated for the full 20 minutes, with commencement of treatment indicated by an arrow. It should be noted that the imagery depicted in Figures 2 and 3 show warm (ship) as darker and cool (wake) as lighter tones in contrast to the ambient sea surface.

Supporting hydrographic and meteorological information was derived from the data summaries of Kaiser (1983) and Kaiser and Munch (1983). The ship wake tracks (Figure 1) are plotted along with a surface temperature field (tidally adjusted) constructed from data obtained from casts with a Neil-Brown conductivity-temperature-depth (CTD) profiles. Phelps Bank and Asia Rip are indicated by the broken line near 69° 20'W. The water temperature at 7m below dead water line (approximate DWL keel depth) was measured with a Plessy Model 6600T thermosalinograph and is plotted in Figure 5 for wakes 2 and 3.

The air temperature measured at 10 meters varied slightly between 15.0 and 15.7°C during the 96 minute transit of wakes 2 and 3. The hydrography of the water column may be characterized by the three STD plots depicted in Figure 4, althought the casts were made several days prior to the wake experiments. As the ship moved eastward on 82-07-14, it encountered an increasingly warm and deepening mixed layer. This is demonstrated by the 7-m-depth temperature data presented in Figure 5.

RESULTS AND DISCUSSION

The Thermal Wake Signature

Thermal IR signatures of natural and oleyl-alcohol treated wake segments are presented together in Figure 2 for comparison purposes. These segments of the turbulent ship wake were generated under similar operating conditions with the ship on a constant heading at essentially constant speed. In general, the environmental parameters remained constant over the time period during which these wakes were produced. The flight altitude was 1500 ft in both cases, and the initiation of wake treatment with oleyl alcohol marked by an arrow was determined from the flight time, the aircraft and ship speeds, and the time of treatment initiation. The length of the treated wake segment depicted in Figure 2 is 3531 m (1.91 nautical miles). The dark broken lines in the image mark 10-second flight intervals. Since the prints of these images were made from original transparencies, the cool surface water of the turbulent wake appears light and the surrounding warmer sea surface is darker, whereas the opposite would be true for the original thermal IR image. The ship's course was approximately 090°, and the wind was 8-12 kts at 045°.

Figure 2. Thermal IR wake signature of <u>USNS HAYES</u>. Top wake at 1747z, 82-07-14, represents 13 min. of treatment with oleyl alcohol. Length of treated wake, 3531 meters (1.91 nautical miles). Lower signature at 1811z, 82-07-14 was of a natural, untreated wake. Both images made from overflights at 1500 feet.

Figure 3. Thermal IR wake signature of USNS HAYES at 1754z, 82-07-14. Wake treated for 20 min. with oleyl alcohol (7.3 mg $\cdot$ m^{-2}); arrow indicates initiation of treatment with organic film-forming agent. Length of treated wake, 5450 meters (2.94 nautical miles). Aircraft altitude 1000 feet.

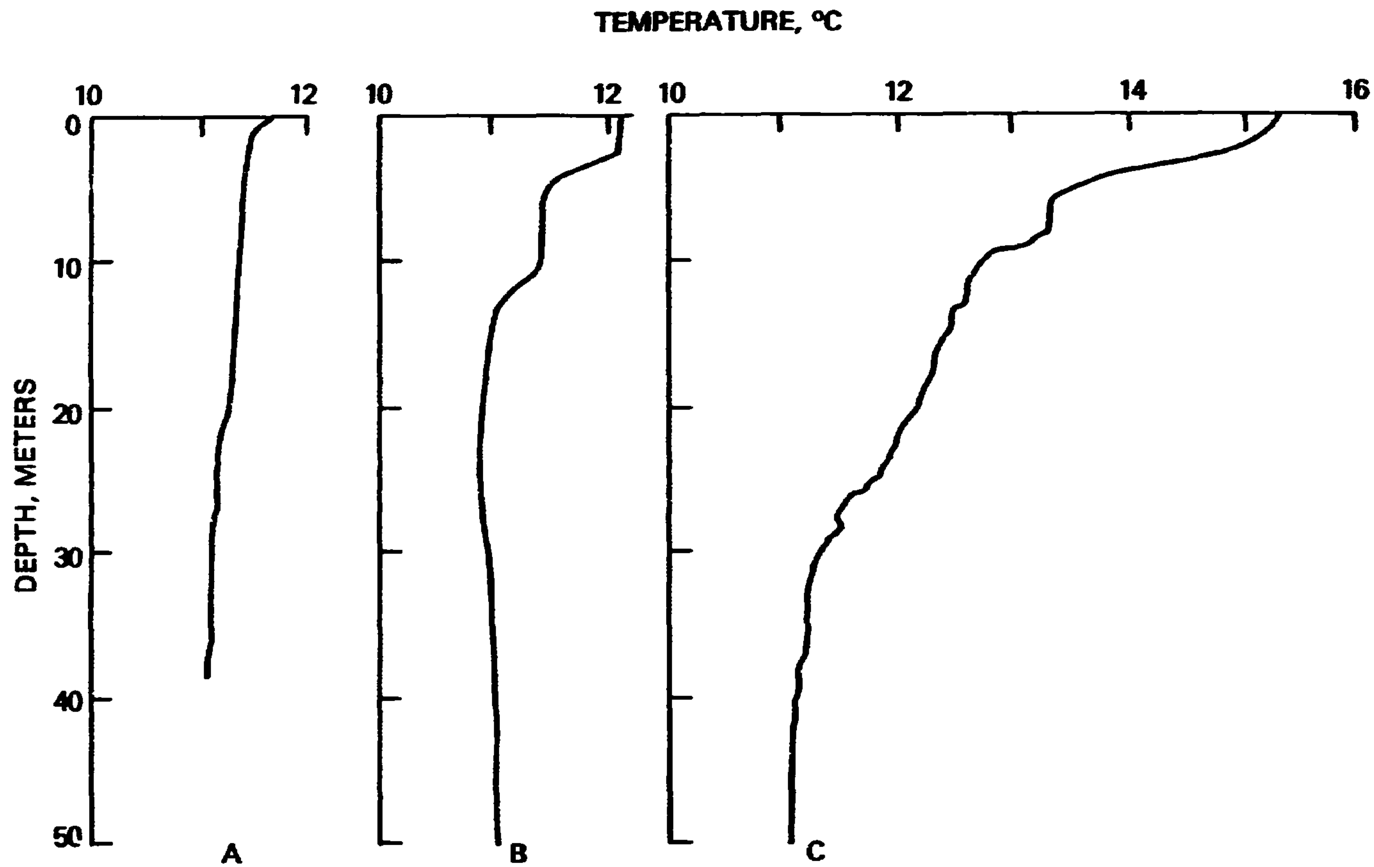

Figure 4. Temperature-depth profiles near wakes 2 and 3. See figure 1 for location. Cast A taken 2329z, 82-07-11, B at 0021z, 82-07-12 and C at 0104z, 82-07-12.

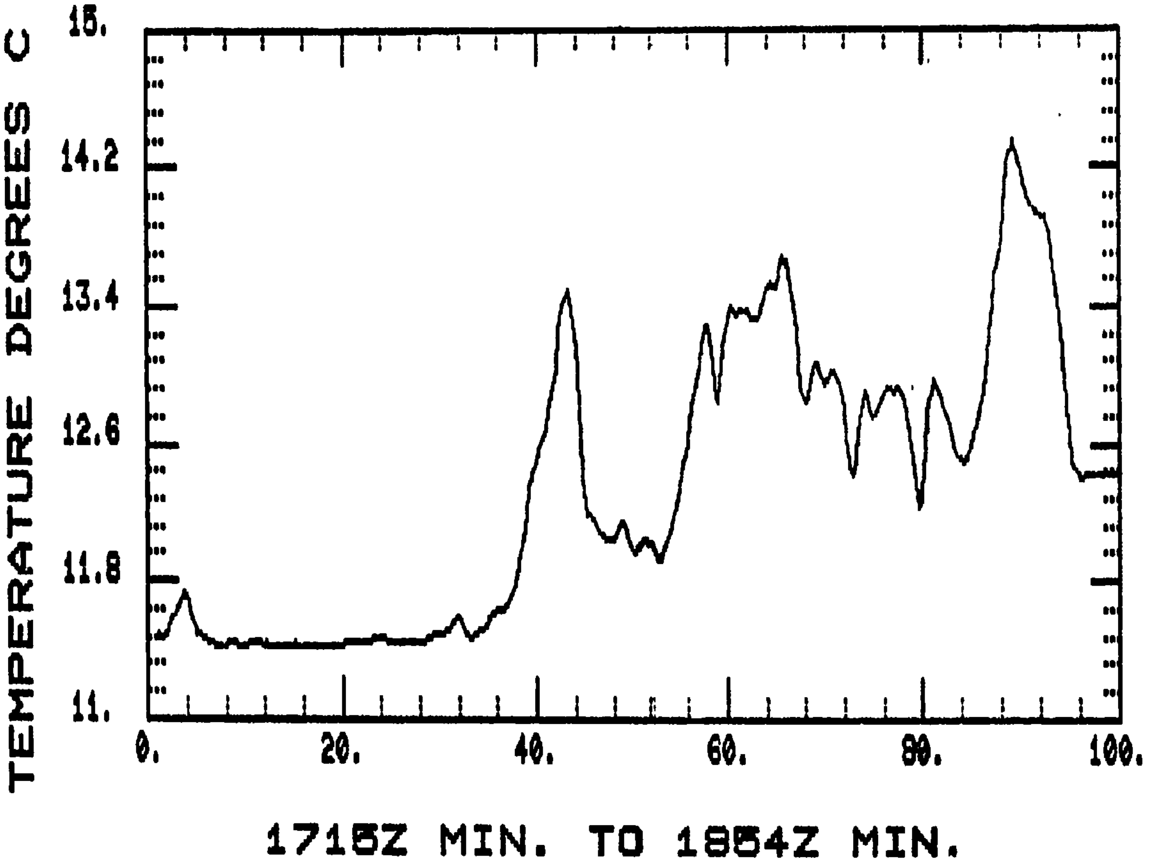

Figure 5. Sea temperature at 7-m depth recorded during wakes 2 and 3.

Visual examination of the two wake-segment images in Figure 2 indicates that the cool ship wake treated with the organic surface film is more intense and persistent than the natural untreated wake. The persistent portion of the treated wake appears to originate at the point of initiation of surface film treatment (arrow). Figure 3 is a thermal IR image of the ship's wake made at 1754z and includes most of the 20 minute surface film treatment of the wake between 1735 and 1755z. In general the thermal signatures of treated wake segments (Figures 2 and 3) are more clearly defined than the natural wakes produced under similar conditions. The reentry of warmer surface water into the cool turbulent wake did not occur as rapidly in the case of the wakes treated with the organic surface film. The organic film resists surface dispersive processes such as wind driven surface flow and the development of small-scale Langmuir circulations.

Thermal surface characteristics were quantified by determining temperature profiles across the wakes using a computer program applied to the digitized wake images. Temperature profiling was performed on the treated and untreated wake signatures depicted in figure 2 at various distances behind the stern of the ship, and the black body reference data were used to assign real temperature values to points of interest on the profiles (Figure 6). Widths of the thermal wake signatures can be determined from the scales at the bottom of the figure. The wind direction can be considered to be from right to left in this data display.

Several significant aspects of the thermal wake signatures derive from the temperature profiles in Figure 6. The cool surface water shows a temperature minimum for both treated and untreated wakes which is nearly the same as the water temperature measured at the 7-m keel depth (see Figure 5). The thermal wake signature data in Figure 6 were taken between 22 to 32 min. (treated with organic film) and 46 to 56 min. (untreated) as indicated in Figure 5. The chemically treated wake was made in slightly cooler keel-depth water than was the untreated wake run made twenty minutes later. The temperature difference between the coolest portion of the wake and the ambient surface (1.5-2.0°C) suggests that upwelling of the subsurface water is responsible for the signal.

In the case of the wake treated with the organic surface film, this temperature difference is too large to be attributed to the film's stabilizing influence on the evaporative-cooled surface boundary layer, an effect which is normally on the order of a few tenths of a degree. However, it is apparent that the wake treated with the monomolecular organic film maintains its cool surface temperature over a broader cross section of the wake, indicating that the immobilized surface layer due to the organic film inhibits the reintroduction of warm ambient surface water from the windward direction. It is also evident from Figure 6 that the thermal wake signature broadens with age, an effect which is more pronounced in the case of the wake treated with the surface film.

Several of the profiles indicate the presence of a slightly warmer band (a few tenths of a degree) which is usually on the upwind outer edge of the turbulent wake. The mechanisms responsible for this warm band and for the other temperature effects are discussed in the ensuing sections on "Wake Hydrodynamics", "Time Evolution of the Wake", and "Effects of Ship Effluents on the Thermal Wake Signature".

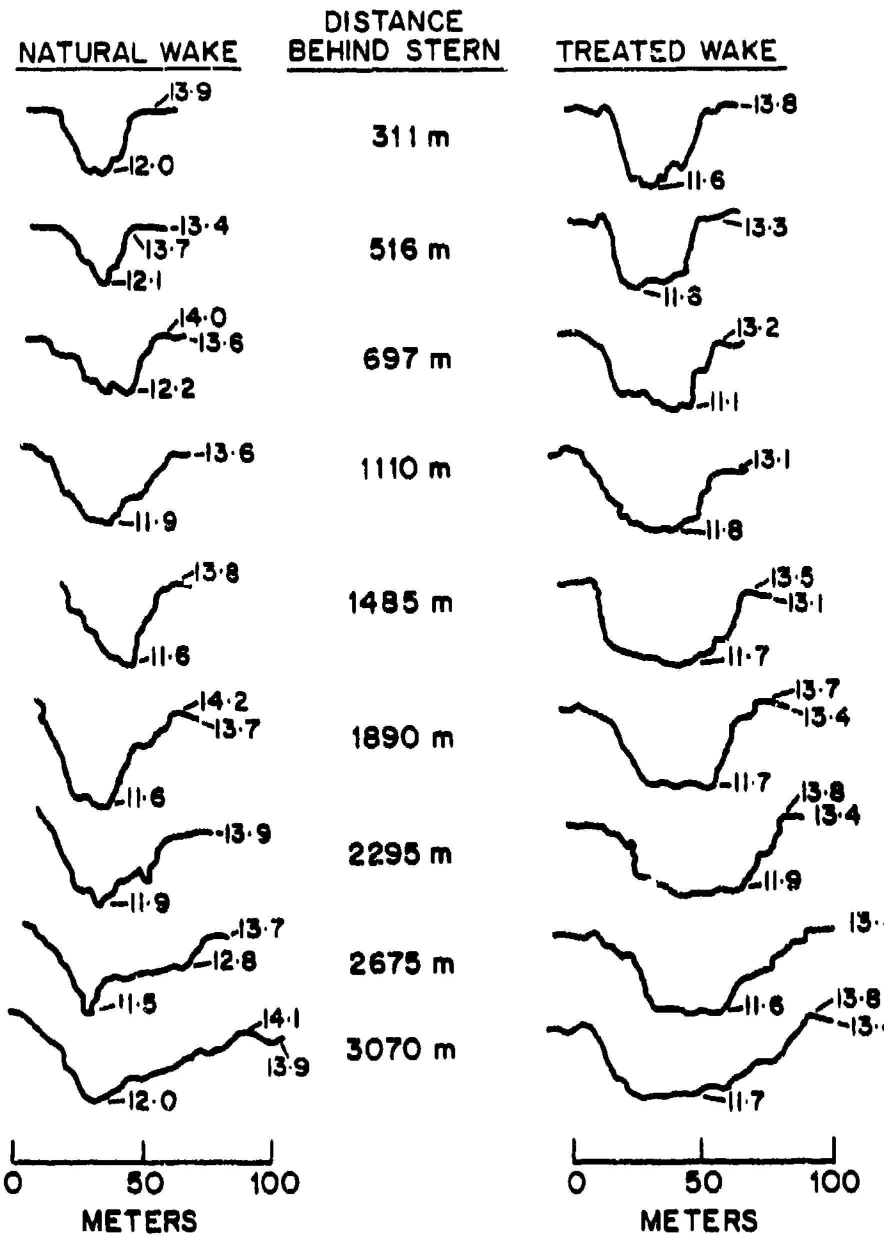

Figure 6. Thermal IR temperature profiles across ship wakes at various distances behind the stern. Natural wake imaged at 1811z, 82-07-14, and wake treated with oleyl alcohol imaged at 1747z, 82-07-14. Reference figure 2.

Wake Hydrodynamics

The hydrodynamics of a ship wake is examined to provide an explanation for the thermal signatures determined in the turbulence wake of the USNS Hayes. As a ship passes through the water, its bow imparts sideways movement to the surface layer of the surrounding fluid. This motion of the surface is maintained by the movement of the widening hull shape through the water. Since the water below the keel is relatively motionless, vortices are generated on either side of the hull (see Figure 7).

After the passage of the ship, the wake can be expected to attain some steady state configuration which would be controlled by the vortex pair generated by the ship (see Figure 8).

In addition, if the water is stably statified and the water within the wake is well-mixed, a wedge of lighter, warmer water will exist on either side of the wake. If the water under these wedges is in hydrostatic equilibrium a gradient in the free surface height must exist, and fluid will move down this gradient toward the lines of convergence marked "A" and "B" in Figure 8.

Garber et al. (1945) have made temperature sections through many ship wakes, and their plots of temperature profile (see Figure 9, for example) provide strong evidence for the existence of convergence zones bordering the wake. Garvine and Monk (1974) describe a similar effect at the boundaries of river plumes.

The cooler, wake water will be driven toward the boundaries by the flow associated with the vortex pair. The strength of the vortices should, then, be a determining factor affecting persistence, since this outward flowing colder water forestalls the intrusion of the warmer ambient fluid. The ship velocity and the hull design determine the vorticity of the surrounding water, and a rapidly moving ship might be expected to leave a more persistent wake than a slower moving ship.

If we consider the fluid beneath the warm wedge to be in hydrostatic equilibrium (Figure 10), we can show the following:

$$\zeta(x) = \frac{\delta\rho}{\rho_1} h(x)$$

where ζ is the free surface elevation, h is the depression of the density interface, and $\delta\rho$ is the change in density across the interface. Since intrusion is enhanced if the slope $\zeta'(x)$ is large, it is concluded that strong density gradients are not conducive to high persistence. The slope of the density interface, $h'(x)$, also plays a role, however $h'(x)$ depends on the vorticity distribution in the wake which cannot be determined without considerable effort and further assumptions. The vorticity distribution also determines the free surface slope within the wake which, in turn, affects persistence.

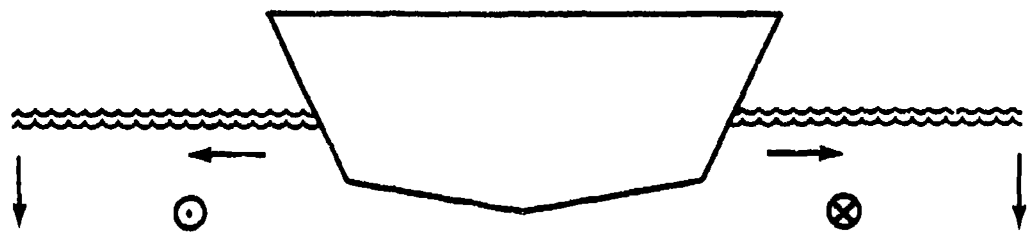

Figure 7. Vortex generation by ship motion. Motion of the hull is assumed into the paper, and . and x indicates the direction of the vorticity vector out of and into the paper respectively.

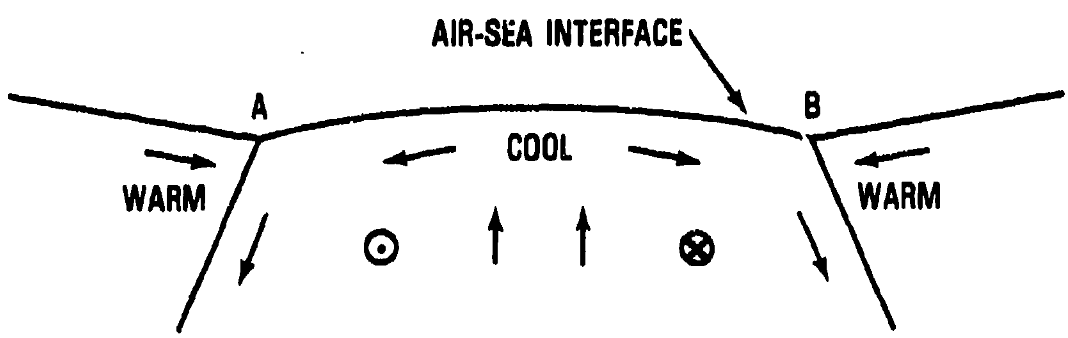

Figure 8. Water mass flow and temperature distribution in a vertical cross section of a ship wake. Lines of convergence exist at A and B.

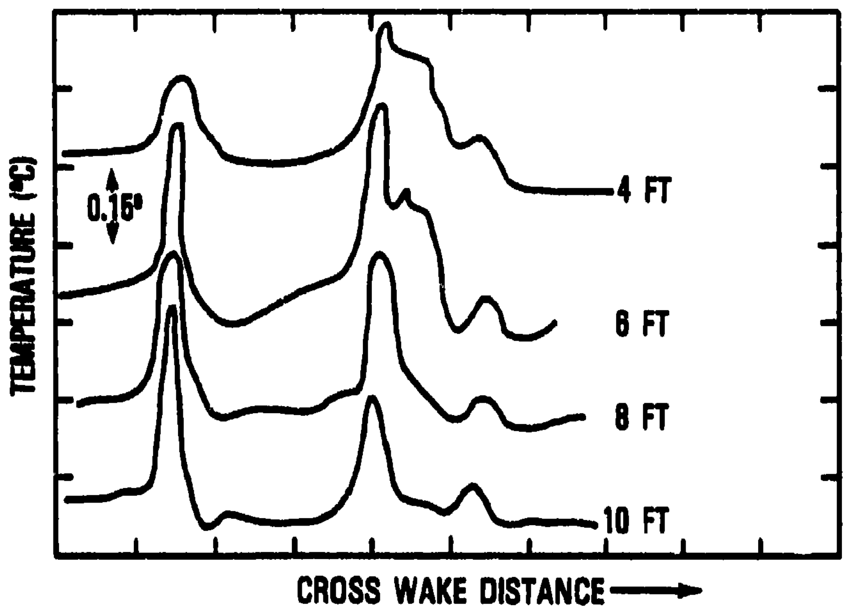

Figure 9. Horizontal temperature structure of a destroyer wake (adapted from Garber et al., 1945). Cross wake distance marks represent approximately 15.4 meters.

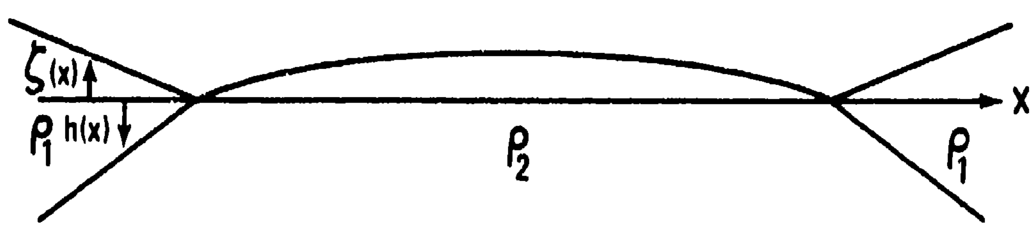

Figure 10. Free suface elevation (ζ) and density interface profile in a vertical cross section of a ship wake.

Another factor affecting persistence is wind stress. A wind blowing across the wake will counter the effect of the slope, $\zeta'(x)$, on the leeward side and enhance intrusion on the windward side. Hence, in many of the IR wake signatures shown in this report the intrusive effects are minimal on the downwind side but marked on the upwind side.

Garber et al. (1945) reported that the wakes measured by them were undetectable when the wakes were less than 30 seconds old. For a ship traveling at a speed of 10 kts this lag translates to a gap of 150 meters behind the ship. A gap can readily be seen in the IR image of the USNS Kane wake, immediately behind the ship (Figure 11). The IR wake of the USNS Hayes, however, displays no characteristic gap behind the hull. The color frontispiece, however, does show evidence of a short (about 10m) dormant stretch of wake directly behind the ship. The cause for the gap must be related to a relaxation time required for the vortex pair to become established. When the ship's stern passes through the water there is an initial rush of converging surface water into the wake. The vortex pair has, until this point, been separated by the hull width. The vortices must now merge to produce the characteristic upwelling that forms the thermal signature of the wake. The absence of a gap behind the USNS Hayes may be explained by the shallow character of the surface thermal gradient or the relatively narrow beam of the twin transoms. Since the stern wakes do not disappear or fade as the ship traverses into deeper water, the latter explanation (hull shape) may be the more promising.

To explain the influence of the additive organic surface film on the persistence of the thermal wake signature, it is necessary to consider effects of the wake motion described above on the monomolecular film. The oleyl alcohol has a density (0.85 $g \cdot cm^{-3}$) which is less than that of the underlying water. It will adsorb at and spread across the sea surface in order to lower the surface free energy (surface tension). The circulation shown in Figure 8 will cause the water-insoluble oleyl alcohol film to concentrate as a coherent film near the boundaries of the wake under the influence of the convergent zones located there. The principal effect of this film layer would be to insulate the convergence zone from the influence of the wind.

The wind stress, τ, is related to the friction velocity, u_*, through the relation,

$$\tau = \rho u_*^2$$

for a neutrally stable atmosphere,

$$V = \frac{u_*}{\kappa} \ln \frac{z}{z_o} \quad ,$$

(Lumley and Panofsky, 1964)

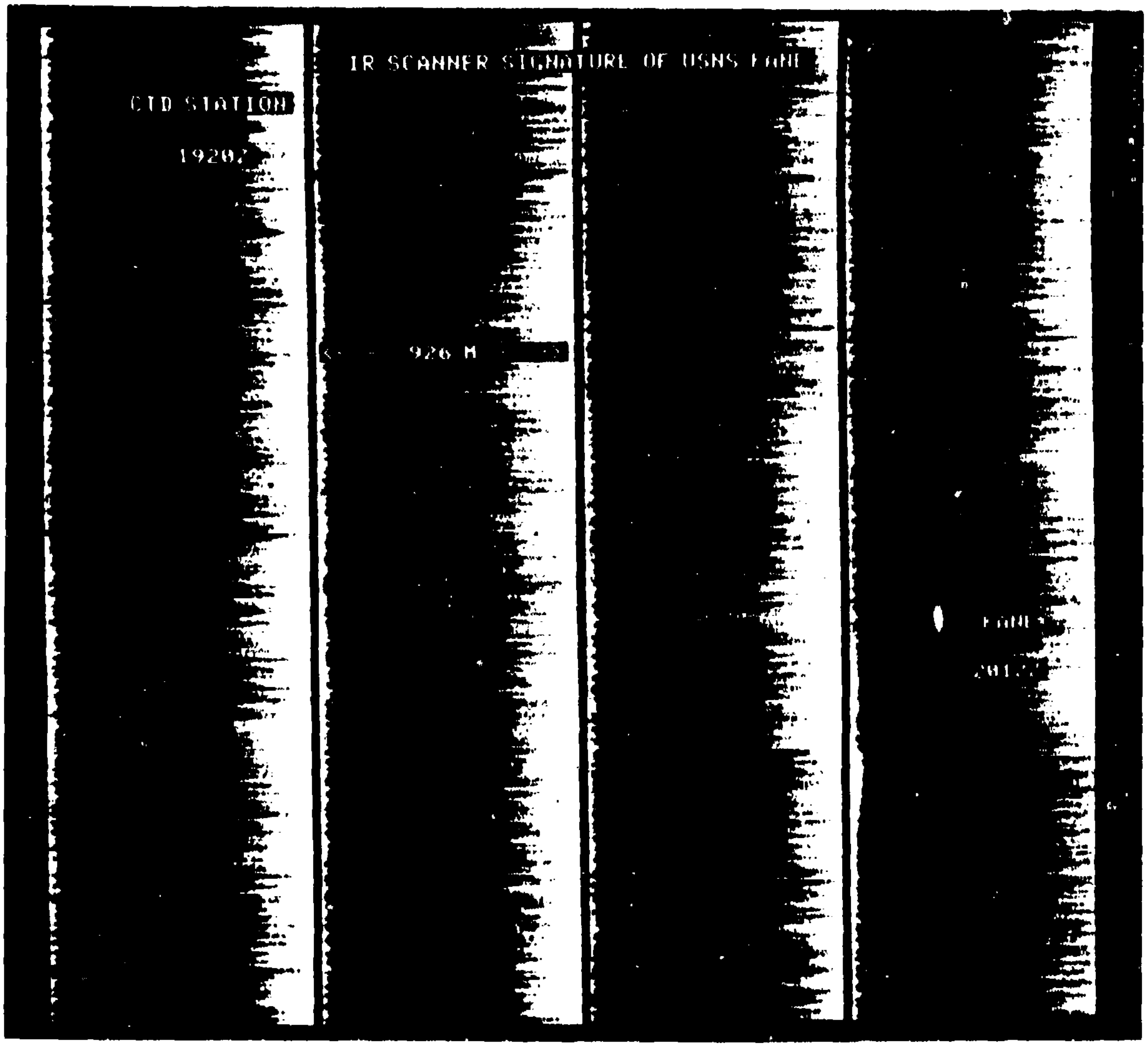

Figure 11. Thermal IR wake signature of USNS KANE overflown 79-09-06 at an altitude of 1500 ft near $30^{\circ}25'$N, $71^{\circ}40'$W in the Sargasso Sea.

where V is the mean wind velocity at height z, and z_o is a measure of the surface roughness, and κ is von Karman's constant. Solving the above equation for u_* we have,

$$u_* = \kappa V \ln \frac{z_o}{z} \quad .$$

so that, for a given wind shear, u_* and τ decrease as z_o decreases. The presence of surface active material such as oleyl alcohol significantly reduces the roughness (z_o) of the surface, and, as a result of the above argument, the surface wind stress is also reduced. Hence, the warm water would not be driven across the interface as readily under the influence of the wind in the presence of the organic film, with the net result that the persistence and definition of the wake would be increased. This effect is demonstrated in Figures 2 and 6.

There is another possible explanation for the persistence of the thermal wake signature under the influence of a continuous organic surface film. Excess oleyl alcohol in equilibrium with its monomolecular film exerts a film pressure of 31 $mN \cdot m^{-1}$. When confined as in the case of the convergence-bounded turbulent ship wake, this surface pressure opposes wind-driven flow from the ambient surface water outside the wake. Using a small-scale wind tunnel Garrett and Barger (1970) measured the minimum wind necessary to overcome the film pressure of various monomolecular films on water contained in an enclosed tray. Motion of the film was indicated by a thin floating hydophobic barrier separating the film-covered and clean water surfaces. An oleyl alcohol film was found to be in equilibrium with an 8·6 $m \cdot sec^{-1}$ wind. Thus, a wind speed greater than this would be required to overcome the film pressure of an oleyl alcohol film in an enclosed situation. Since winds during the wake experiment were less than the equilibrium velocity, the resistance of the film to wind-driven surface flow could explain the persistence of the thermal wake features if the film was essentially continuous within the area bounded by the convergences at the outer edges of the turbulent wake.

Time Evolution of the Wake

The thermal wake broadens with time as the upwelled cooler water is drawn toward the convergent boundaries of the hydrodynamic wake. However, as the wind stress drives warm surface water across the upwind wake boundary, the width of the thermal wake reaches a steady state value and then begins to decrease. Figure 12 is a time series of three images taken of a film-treated wake overflown at 1754z on 82-07-14. The time interval between passes is about 7.5 minutes. After the first 7.5 minutes the downwind boundary starts to become more sharply defined as the cool upwelling water is driven against the leeward convergence line. The upwind boundary begins, to lose definition as warm surface water is driven into the wake by the wind. Finally, after 15 minutes, the upwind boundary completely gives way to warm water intursions. Figure 13, a section of untreated wake, shows evidence of the warm line of convergence on the windward side of the wake. This line has high along-wake coherence compared to the along-wake structure of the cooler water.

Figure 12. Time-lapse images of <u>USNS HAYES</u> wake treated with oleyl alcohol. Wake age interval between image is approximately 7.5 minutes.

Figure 13. Thermal IR image of natural, untreated portion of wake of USNS HAYES at 1812z on 82-07-14.

Ship Effluents and the Thermal Wake Signature

Various types of organic film-forming material may be inadvertently or intentionally discharged from a ship into its wake. These include oily substances from bilge pumping or from galley and sewage discharges. In addition, used lubricating and hydraulic oils are sometimes pumped overboard. Galley effluents, such as fats or glyceride esters (cooking oils), may spread into thin, nearly monomolecular films which would modify the thermal wake characteristics in a manner similar to that of the oleyl alcohol used in this research. Petroleum oils, on the other hand, form multilayered films with variable thickness which may have either warmer or cooler thermal IR signatures than that of the surrounding sea surface.

When a petroleum oil is spilled onto the water surface it usually spreads rapidly under the influence of both gravitational and surface chemical effects. The polar, surface constituents of the oil (compounds containing nitrogen, oxygen and sulfur) are highly influential in spreading the spill into extremely thin layers that approach monomolecular dimensions at the outer edges of the oil slick (NAS, 1975; Garrett, 1974). On calm water the thicker regions of a spill may eventually separate into a number of thick-film segments separated by thinner oily layers, while on a wind-driven sea, bands of thick layers form which become aligned approximately with the wind direction. In all cases, as long as the spill remains in a fluid, spreadable condition, its surface-active constituents spread over the water surface and create thinner layers around the thick films of oil. For example, Hollinger and Mennella (1973) demonstrated that, after several hours following a spill of No. 2 fuel oil, 90% of the oil was found in 10% of the area of the resulting slick. Most of the spread fuel-oil film was very thin (less than 0.1 mm), with the thicker portion surrounded by progressively thinner layers.

Information derived from thermal infrared signatures of oil spills and experimental oil discharges onto the sea can be used to predict thermal signatures of petroleum oils in ship wakes. Subsurface oil released during the Santa Barbara oil spill episode of 1969 was imaged with an 8-14 micrometer thermal IR mapper (Estes and Golomb, 1970). A complex pattern of signatures were associated with the oil released onto the water in the Santa Barbara Channel which were both lighter (warmer) and darker (cooler) than the ambient sea surface. Cool signatures were attributed to both thin and thick oil films, while very bright (warm) streaks were identified as streamers of thick oil.

It was theorized that crude oil should produce a lighter tone on a thermal infrared image scan, as was the case for the thick oil streaks mentioned previously, because being darker than ambient sea water, oil should have a higher emissivity. To the contrary, the reflectivity of petroleum films and the interference with heat exchange at the air-sea interface might lead to an expectation of cooler tones on the thermal infrared image. The thick streaked oil films were bright (warm) as expected on the basis of emissivity considerations. However, a large thick film of oil near the oil-well blowout site was dark (cool) in the image. This latter effect represented a special case where cooler subsurface fluids were displacing the warmer surface waters. The thinner oil layers surrounding

the main body of oil were generally cool. The explanation of the cool signature was that the iridescence of the thinned oil makes the film a better reflector, and that the oil layer reduces heat exchange across the air-water boundary. In addition, it is likely that the very thin, nearly monomolecular slick at the outermost edge of an oil spill will appear slightly cooler than the ambient sea surface, even though it has no iridescence and has little thickness. Like natural surface films this slight cooling effect is due to an immobilization of the evaporation-cooled surface layer by the thin film of petroleum. Swaby and Forziati (1969) also reported that IR imagery of a small experimental oil spill indicated warm signatures for the thicker portions of the spread oil and cool value for the thinner layers in comparison with the surrounding sea water surface. In this study there was no upwelling from below to producue a "cool" image for the thicker oil layer as was observed for segments of the oil slick from the Santa Barbara blowout.

It is expected that the thermal signatures of petroleum oils in ship wakes will be related to oil-layer thickness as described in the foregoing discussion. It should be noted that effluent ship oils are free to spread along the major axis of the turbulent ship wake. In addition, oils dispensed from the stern are confined to the water surface within the wake by the surface convergent forces associated with wake dynamics. In general, it is not expected that the rate of overboard discharge would be sufficiently high to cover the sea surface area of the wake with a thick enough layer of oil to produce a warm thermal IR signature. However, if there is sufficient pollutant oil to cover the thermally modified area of the ship wake, the persistence of the wake signature could be dramatically increased by the following mechanisms, (1) the thermal signature caused by the oil itself, and (2) the prevention of the reentry of warmer ambient surface water into the cool wake.

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